

Mg DIFFUSION IN ANORTHITE: SURVIVAL OF THE ^{26}Al CHRONOMETER. T. LaTourrette* and G. J. Wasserburg, Lunatic Asylum, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, CA 91125. *Now at: Department of Earth & Space Sciences, UCLA, Los Angeles, CA 90095-1567; tlat@ess.ucla.edu.

INTRODUCTION: The presence of excess ^{26}Mg (from the decay of short-lived ^{26}Al) provides key constraints on the time interval between ^{26}Al production in the interstellar medium and the formation of early solar system objects. Insofar as $^{26}\text{Al}/^{27}\text{Al}$ was initially uniform throughout the solar system, the ^{26}Al - ^{26}Mg system can serve as a chronometer for events in the early solar system. Measurements in melted objects show that $(^{26}\text{Al}/^{27}\text{Al})_0$ (initial ratio) lies between $\sim 5 \times 10^{-5}$ and ~ 0 [1], with CAIs commonly showing values near 5×10^{-5} . In contrast, Al-rich chondrules typically show no evidence for ^{26}Al , although a growing body of data clearly shows that some had $(^{26}\text{Al}/^{27}\text{Al})_0 \sim 10^{-6}$ [2]. If $^{26}\text{Al}/^{27}\text{Al}$ was initially uniform throughout the solar system, the large range in $(^{26}\text{Al}/^{27}\text{Al})_0$ indicates that CAI and chondrule formation spanned $\gtrsim 5$ Ma. A potential complication with this interpretation, however, is post-crystallization redistribution of Mg such as might occur during thermal metamorphism on protoplanets. In this case the ^{26}Al - ^{26}Mg systematics would give no time information. Excess ^{26}Mg can thus far only be resolved in phases with Al/Mg $\gtrsim 10$, such as plagioclase. No data for Mg diffusion in plagioclase exist, however, and previous estimates of Mg diffusivity have been based on data for Sr. Here we present the first measurements of Mg self diffusion in anorthite. We then use these data to calculate the conditions under which Mg will isotopically exchange with surrounding phases and thus establish bounds on the thermal conditions required to preserve or destroy the ^{26}Al chronometer in anorthite.

EXPERIMENTS: Self diffusion coefficients for Mg, Ca, and Sr were measured in anorthite (An_{95}) from Miyake-Zima, Japan. Diffusion couples were prepared from sections of oriented single crystals and synthetic, isotopically enriched anorthite glass. The major and trace element composition of the glass is identical to that of the anorthite crystals, while the isotopic fractions of ^{25}Mg , ^{44}Ca , and ^{86}Sr are enriched by factors of 2-5 relative to the natural fractions in the crystals. Homogeneous, bubble-free glass was melted into short Pt capsules, ground flat, and polished. $\sim 2 \times 2 \times 1$ mm sections of crack-free and nominally inclusion-free anorthite crystals were polished and then annealed overnight to heal surface damage incurred during preparation. Crystals and glass capsules were then tightly joined with a thin Pt band and annealed at the desired temperature at atmospheric pressure in air for 3-30 days. Quenched charges were sectioned perpendicular to the diffusion interface and isotopic concentration profiles were measured with the Panurge ion microprobe. The annealed couples displayed a featureless, well bonded interface, indicating a wetted contact between the crystal and glass. The glass quickly devitrifies to a feathery mass of plagioclase crystals, so diffusion occurs between single

crystal and microcrystalline (\pm glass) anorthite.

When the total concentration of the diffusing element is constant across the couple, the solution to the diffusion equation for the crystal side of the couple is
$$iR = \frac{(iR_x + iR_g)}{1 +} + \frac{(iR_g - iR_x)}{1 +} \text{erf} \frac{x}{2\sqrt{D_x t}},$$
 where iR = the

atom fraction of the diffusing isotope, i (i.e., $iR = iC/kC$), where the sum is taken over all k isotopes of an element), iR_x and iR_g are the fractions of i in the single crystal and microcrystalline mass far from the interface, x = distance, t = time, D_x = the diffusion coefficient in the single crystal, D_g = the effective diffusion coefficient in the microcrystalline mass, and $\sqrt{D_g/D_x}$ [3,4]. Diffusion coefficients for the single crystal were recovered from the measured profiles by fitting the data to the above equation. In all cases fits are excellent. Typical profiles are shown in Fig. 1. Although this technique allows separate diffusion coefficients to be recovered from each half of the couple [4], values determined for the microcrystalline half are highly variable. We interpret this to result from variable grain sizes and varying degrees of devitrification.

RESULTS: Several profiles, ranging from 10-150 μm in length, were measured in each experiment. For Mg and Ca, the range in diffusion coefficients determined from separate profiles is generally very small ($\pm 20\%$), and serves as a preliminary estimate of the uncertainty. Sr shows more variability, as the length of the diffusion profiles approaches the limit of spatial resolution for an ion probe traverse. Our Sr diffusion coefficients agree with previous high temperature measurements to within a factor of 2 [5], but our activation energy is almost a factor of 2 lower. This may indicate that the uncertainty of our D_{Sr} values is about a factor of 2. Diffusion coefficients for Mg and Ca, however, are well defined and give reasonable activation energies (see Table). Results for diffusion normal to (010) are listed in the table and illustrated in Fig. 2. Initial results indicate that diffusion normal to (001) is approximately a factor of 2 faster. The measured diffusion coefficients show a very strong dependence upon ionic radius, with $D_{\text{Mg}}/D_{\text{Sr}} = 60-235$. This result clearly demonstrates that the diffusion coefficient of Mg in anorthite cannot be approximated with that for Sr.

DISCUSSION: Using the Arrhenius parameters for Mg diffusion in anorthite, we calculated the thermal history required to completely erase a signature of excess ^{26}Mg in anorthite for three different thermal models (Fig. 3). All models assume spherical diffusion (solutions for spheres and long cylinders agree to within a factor of 2) and that the minerals surrounding the anorthite act as an infinite sink for Mg. For the simplest case of isothermal annealing, excess ^{26}Mg in a 25 μm radius anorthite crystal will be erased in ~ 1.2 Ma at 600 $^{\circ}\text{C}$ (Fig. 3a), and the

minimum temperature required for Mg isotopic homogenization over the age of the solar system is 450 °C. Two cases of slow cooling were modeled. To completely erase ²⁶Mg excesses in a 25 μm anorthite initially at 600 °C, exponential cooling [6] requires an initial (maximum) cooling rate of <2x10⁻⁵ °C/y (Fig. 3b), and burial in a regolith followed by conductive cooling [7] requires a burial depth of >1 km (Fig. 3c).

Although these calculations are susceptible to uncertainties stemming from the large down-temperature extrapolations, they provide the first estimate of the temperature history required to reset the ²⁶Al chronometer in anorthite. If chondrites are assembled in bodies of ~10

km radius at an initial temperature of ~600 °C, then over 70% of the mass of the parent body will have isotopically normal plagioclase (for r = 25 μm). Thermal resetting is thus a viable interpretation of the lack of ²⁶Mg anomalies in many cases. Conversely, complete preservation of ²⁶Mg anomalies requires a maximum metamorphic temperature of ≤450 °C.

Self Diffusion Normal to (010) (cm ² /s)			
	Mg	Ca	Sr
D ₀	1.5x10 ⁻²	1.3x10 ⁻⁵	2.6x10 ⁻⁹
E (kJ/m)	292	236	148

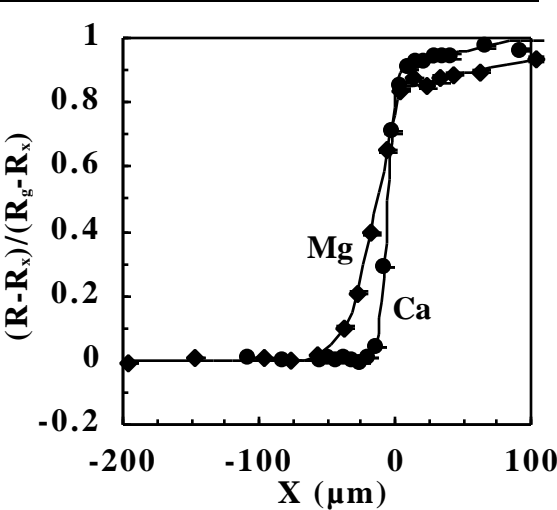


Figure 1. Normalized Mg and Ca isotopic profiles and best fit diffusion curves across single crystal-microcrystalline (±glass) anorthite couple run at 1300 °C for 12 days.

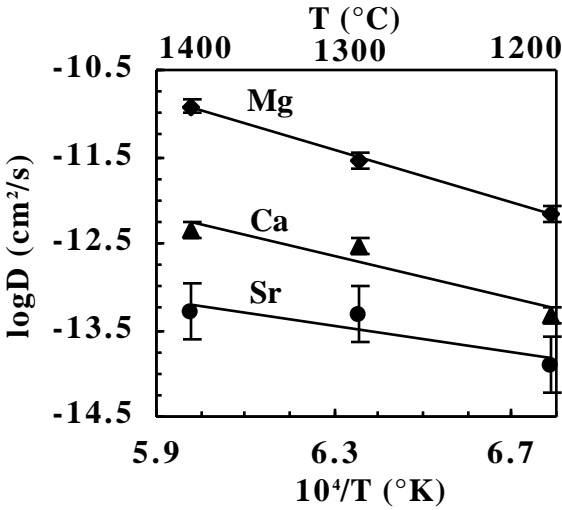


Figure 2. Temperature dependence of Mg, Ca, and Sr, self diffusion coefficients in anorthite. Uncertainty is ±20% for Mg and Ca and ±100% for Sr. Derived Arrhenius parameters are listed in Table.

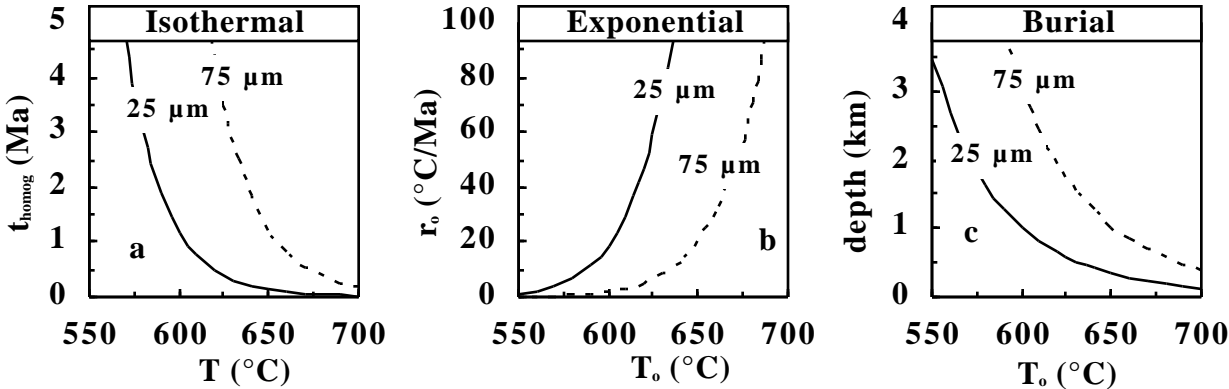


Figure 3. Fate of the ²⁶Al chronometer in anorthitic plagioclase in response to heating. Only points lying to the left of the curve for a given crystal radius may partially preserve ²⁶Mg anomalies; points to the right will be completely reset. (a) Time vs. temp. for isothermal heating. (b) Initial cooling rate vs. initial temp. for exponential cooling [6]. (c) Burial depth vs. initial temp. for conductive cooling beneath a regolith blanket with $\kappa = 10^{-8}$ m²/s and surface T = 0 °C [7].

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